An Investigation of the Accuracy and Reproducibility of 3D Printed Transparent Endodontic Blocks

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ABSTRACT

Due to a broad spectrum of endodontic rotary instruments on the market and no standardised protocol for comparing their mechanical properties, it can be challenging for clinician to choose proper instruments. In vitro studies using resin blocks with artificial canals can offer many valuable information because of their uniformity compared to studies performed on extracted teeth. To improve precision and reproducibility of artificial canals, 3D printing was used in this study to manufacture endodontic test block samples. 20 commercially available endodontic blocks Endo-Training-Bloc-J by Dentsply Sirona were tested. The mean values of the measured parameters were used for a 3D CAD model of their replicas. 20 copies of the endodontic training blocks were printed from acrylic resin (VeroClear-RGD810, Stratasys, Eden Prairie, USA) using the 3D printer Objet30 Pro (Stratasys, Eden Prairie, USA). The key dimensions of the commercial blocks and the 3D printed blocks were measured under and compared using *t* – test and Levene's test for equality of variances. The profiles of the 3D printed artificial canals showed significantly lower dimensional variability when compared with the commercial blocks. 3D polyjet printing proved to be a precise and reproducible method for production of blocks for testing endodontic rotary instruments.

KEYWORDS

endodontic training block; 3D printing; additive manufacturing; artificial root canal; J shape resin block; PolyJet printing

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Received: 1 July 2022
Accepted: 8 September 2022
Published online: 2 December 2022

Acta Medica (Hradec Králové) 2022; 65(2): 59–65
https://doi.org/10.14712/18059694.2022.19

INTRODUCTION

Maintaining the original anatomy of a root canal during preparation is one of the goals of the root canal treatment. It is challenging especially in curved canals (1). To achieve this goal, NiTi (nickel-titanium) systems using the superelastic properties of the nickel-titanium alloy have been introduced. NiTi rotary instruments are more flexible, and preparation is less time consuming when compared with stainless steel instruments (2). Probably the biggest disadvantage of this type of treatment is a risk of an abrupt separation of a tip of the instrument. This can prevent proper irrigation of a system of root canals and subsequently jeopardize the success of root canal treatment (3). Many NiTi endodontic systems came to the market during last decades and choosing proper system is essential for every clinical situation. Changing parameters, such as different cross section, conicity, surface treatment, can improve the performance of NiTi instruments (4, 5). Some procedures as heat treatment of alloy are proprietary (6).

There is no standardised protocol that compares properties of NiTi endodontic instruments. Some studies used extracted teeth to better simulate clinical situation but range of variations in the anatomy of root canals of teeth makes the study results difficult to interpret and reproduce (7, 8). Therefore, some other studies used artificial canals made of clear cast resin for their uniformity (9, 10). Transparent simulated root canal models also allow for overlapping pre- and post- instrumentation images to evaluate the preparation (11). However, the artificial root canals lack anatomical irregularities, three-dimensional curvatures, and other qualities of clinical situation. The market offers only few variations in the shape of a canal. Furthermore, the conventionally manufactured simulated root canal models have production-related deviations, so even these models are not sufficiently identical and lack standardization (12, 13). Nevertheless, the resin blocks are broadly used not only in theoretical studies but also for endodontic training, educational purposes, and laboratory assessment of qualities of endodontic instruments, where it is essential to have precise morphology of the artificial root canal. There are many classification systems describing root morphology. Cross-sectional shapes include round, oval, round oval, ribbon, irregular and C-shaped canals (14). Shape of root curvature can be classified as straight, J-shaped, entirely curved and S-shaped (15). For most purposes, the J-shaped artificial canals with round cross-section are the most relevant ones due to widely established test methodology (9, 11, 16). A commercially available endodontic block with J-shape round cross-section artificial canal with dimensions corresponding to the average physiological dimensions of the root canal is Endo-Training-Bloc-J by Dentsply Sirona.

The advance in the additive manufacturing makes it possible to create transparent endodontic blocks with artificial root canals of any conceivable shape with sufficient accuracy and reproducibility (17, 18). Current drop on drop 3D techniques allows for printing objects with resolution of 16 μm per layer. However, to this date, there is no study that has properly analysed the J-shaped endodontic training block and 3D printed its replica. The aim of this study was to investigate the possibilities of 3D printing of endodontic blocks with artificial root canals using the 3D printer Object 30 by Stratasys Ltd. and to compare the accuracy and reproducibility of the 3D printed endodontic blocks (further referred to as the 3DP blocks) with the conventional commercially available endodontic blocks Endo-Training-Bloc-J by Dentsply Sirona (further referred to as the original resin blocks).

MATERIALS AND METHODS

A total of 20 ready-made transparent epoxy resin blocks – Plastic Practice Blocks .02 taper – Oblong for 15 file (Endo-Training-Bloc-J Dentsply Sirona, Ballaigues, Switzerland) were photographed under binocular microscope (DSZS 1112-300, Arsenal, Prague, Czech Republic). The key parameters of the artificial canals, i.e., the Canal profile, Canal thin, Canal thick, Cone length, Canal angle, Cone angle, and Pitch angle, shown in Figure 1, were measured with the help of NIS-Elements 3.20 (Nikon Instruments Inc., Melville NY, USA). The canal profile is defined by the perpendicular distances from the base line, measured at 100 to 1000 pixels positions with the help of the 100 × 100-pixel grid. The base line is the line tangent to the output cylinder surface, starting at point where the thin tip of the canal intersects this surface (Figure 1).

The mean value of each parameter was used to design 3D drawings in CAD software (Cloud Powered 3D CAD/CAM Software for Product Design | Fusion 360, 2018, Autodesk, San Rafael, USA). Subsequently, 20 prototypes of endo blocks were printed from acrylic resin (VeroClear-RGD810, Stratasys, Eden Prairie, USA) using the 3D precision printer Objet30 Pro (Stratasys, Eden Prairie, USA). The Objet30 Pro uses the so called PolyJet or Drop on drop printing process where the object is built by selective spraying drops of a photopolymer in ultra-thin layers. Each photopolymer layer is cured with UV light after it is jetted, producing fully cured models that can be handled and used immediately, without post-curing (19).

High printing precision with the layer thickness of 16 μm was used. The printer used a soluble support material (SUP706B, Stratasys, Eden Prairie, USA), which should allow for hands-free, water-jet removal without damaging the delicate structures. A combined glossy, for transparent outer walls, and matte, for precise inner structures, printing technique was used. This should allow to observe the printed inner artificial canal structure through the transparent wall. To enhance optical properties of the transparent wall eliminating the undesirable light scattering on the still rough surface of the resin block, Evetric Bond (Ivoclar Vivadent AG, Schaan, Liechtenstein) with straight stainless steel dental matrix were used to create smooth surface and improve the transparency.

The printed prototypes were then instrumented using ISO 10 stainless steel K-file (Micro-Mega, Besançon, France) and ethanol 96% as irrigation to remove the soluble support material (SUP706B, Stratasys, Eden Prairie, USA).

The same procedure of measuring as for manufactured models was used for these prototypes. However, due to a small shift in the focal plane of the 3DP blocks relative to the original resin blocks, a difference in the micrograph

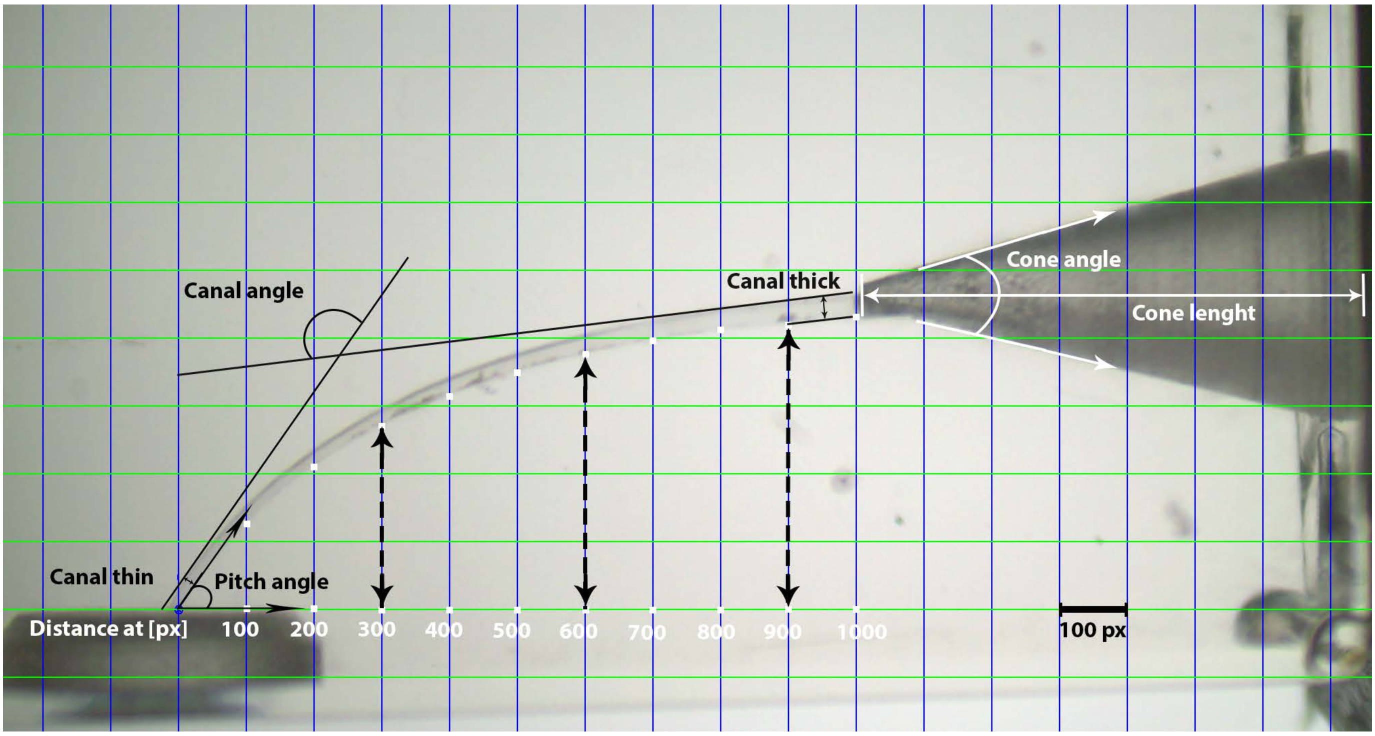

Fig. 1 3D printed block with highlighted measured parameters. 100 pixels correspond to a distance of 743.8 μm.

calibration occurred between the original and the 3DP block, i.e., 100 pixels in the micrographs of the original resin blocks corresponds to 852.2 μm while 100 pixels in the micrographs of the 3DP blocks corresponds to 743.8 μm. This mismatch led to a different "true positions", at which the canal profile was measured, and need for fitting the original profile values with a polynomial function to calculate the profile values as if measured at the true positions in the 3DP micrographs. For this purpose, the profile data of the original blocks were fitted with a fourth-degree polynomial using the MS Excel 2016 (Microsoft Corp., Redmond WA, USA) polynomial trend line function. Nevertheless, as all the micrographs were calibrated using the same calibration slide, the measured distances were not affected.

The results were compared, processed, and statistically analysed using MS Excel 2016 (Microsoft Corp., Redmond WA, USA) and NCSS 10 statistical software (2015, NCSS, LLC., Kaysville, Utah, USA, ncss.com/software/ncss). Since all the data showed to be from normally distributed populations, we opted for using the mean and standard deviation of the sample (± SD) for the data description. We tested the printing accuracy by comparing the printed blocks' parameters with the values used in the 3D CAD design using 1-sample t-test. We compared the reproducibility of the commercially available endodontic blocks (Endo-Training-Bloc-J Dentsply Sirona, Ballaigues, Switzerland) with the printed blocks using Levene's test for equality of variances. In all the tests, a value of $p < 0.05$ was considered as significant.

RESULTS

Table 1 shows the measured key parameters of the original resin blocks and the corresponding rounded values used as an input for the CAD model of the 3D printed blocks (available in the supplementary materials on the article web page). For the comparison purposes of the original resin blocks with the 3DP blocks, Table 1 also shows the corrected values of the original resin blocks obtained using the fitted fourth-degree polynomial function. The course of the function and its parameters are shown in Figure 2.

Table 2 shows the measured key parameters of the 3D printed blocks. When compared with the original resin blocks, the artificial canal profiles of the 3D printed blocks have significantly lower dimensional variability as shown by the results of the Levene's test (Table 3). The dimensional variability of the 3D printed blocks represented by coefficients of variation (Table 2) was 2 – 5 x lower than the variability of the original resin blocks (Table 3).

All the measured values of the canal profile of the 3D printed blocks were significantly different compared to the original resin blocks as proved by the t – test (one sample t – test, Table 3). The larger the measured profile value, the larger the observed difference. The maximum profile difference was observed at the "true" position of 7438 μm where the mean measured 3DP block profile value was by 8% smaller (Ratio of Means 3DP / Original, Table 3) than the corresponding profile value of the original resin block.

Apart from the Canal thin parameter, the other monitored parameters also differed significantly (one sample t – test, Table 3). Considering the data variability, the Canal thin, Canal thick Canal angle, and Pitch angle of the 3DP block did not differ significantly from the original resin block. Only in the case of the cone angle parameter, the variability of the measured data of the 3DP block was significantly larger, more than four times (Coefficient of Variation ratio 3DP / Original, Table 3), than that of the original resin block.

Tab. 1 Key parameters of the original epoxy resin block – Plastic Practice Blocks .02 taper – Oblong for 15 file (Endo-Training-Bloc-J Dentsply Sirona, Ballaigues, Switzerland) – [1]) measured values, [2]) rounded mean values used as the input for the CAD model (available in the supplementary materials on the article web page), and [3]) corrected values used for comparison purposes.

dimension			Original block[1] (μm)	Coefficient of Variation[1] (%)	Model input	
	(pixel)	true position (μm)			Original[2] (μm)	Corrected[3] (μm)
Canal profile	@ 100px	@ 852.1 μm	1208.0 ± 85.3	7.06	1208.0	1090.4
	@ 200px	@ 1704.3 μm	1954.3 ± 120.3	6.15	1954.3	1791.1
	@ 300px	@ 2556.5 μm	2467.8 ± 130.4	5.28	2467.8	2296.4
	@ 400px	@ 3408.6 μm	2820.9 ± 136.6	4.84	2820.9	2658.1
	@ 500px	@ 4260.8 μm	3065.1 ± 130.6	4.26	3065.1	2918.5
	@ 600px	@ 5112.9 μm	3249.4 ± 121.3	3.73	3249.4	3111.2
	@ 700px	@ 5965.0 μm	3381.4 ± 110.2	3.26	3381.4	3260.6
	@ 800px	@ 6817.2 μm	3481.8 ± 99.8	2.87	3481.8	3382.0
	@ 900px	@ 7669.3 μm	3590.8 ± 220.3	6.14	3590.8	3481.9
	@ 1000px	@ 8521.5 μm	3592.6 ± 82.2	2.29	3592.6	3557.4
Canal thin			136.9 ± 11.3	8.24	136.9	–
Canal thick			314.3 ± 15.2	4.84	314.3	–
Cone length			6033.4 ± 196.7	3.26	6033.4	–
			(deg)	**(%)**	**(deg)**	–
Canal angle			125.5 ± 2.8	2.22	125.5	–
Cone angle			29.4 ± 0.3	1.01	29.4	–
Pitch angle			58.2 ± 2.2	3.74	58.2	–

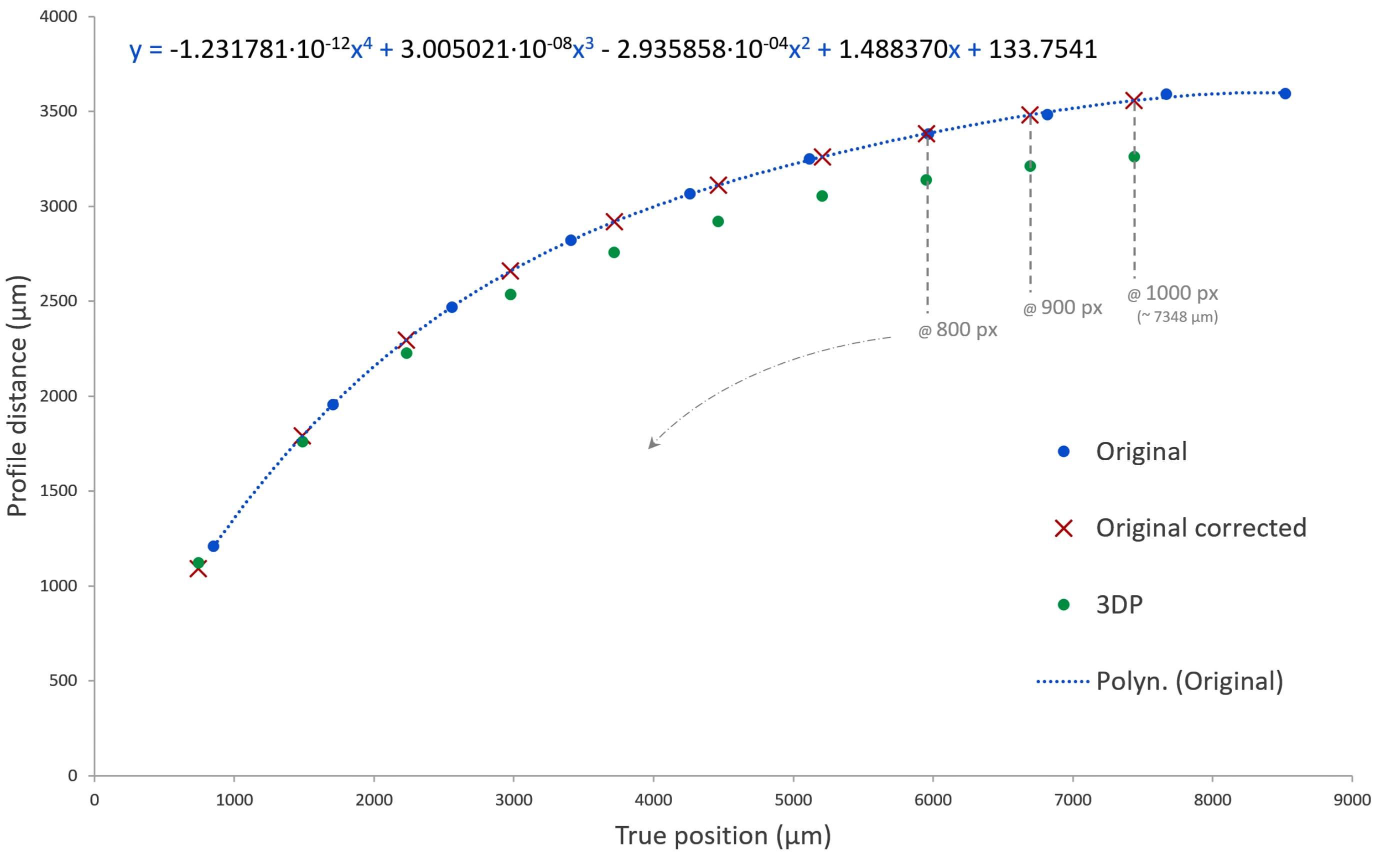

Fig. 2 Profile data of the artificial canals. The blue dots indicate the means of the measured profile data of the original blocks, the red crosses mark the corrected profile data of the original blocks as if measured at the same "true" positions as the 3DP blocks, the green dots indicate the means of the measured profile data of the 3DP blocks, and the blue dotted line depicts the fitted fourth–degree polynomial function. The formula represents the fourth–degree polynomial function fitted on the mean profile data of the original blocks with the resulting function parameters.

Tab. 2 Key parameters of the 3D printed endodontic blocks.

dimension			3DP block (µm)	Coefficient of Variation (%)
	(pixel)	true position (µm)		
Canal profile	@ 100px	@ 743.8 µm	1121.0 ± 47.7	4.26
	@ 200px	@ 1487.6 µm	1759.3 ± 41.1	2.34
	@ 300px	@ 2231.4 µm	2225.8 ± 34.7	1.56
	@ 400px	@ 2975.2 µm	2535.9 ± 30.7	1.21
	@ 500px	@ 3719.0 µm	2756.9 ± 34.3	1.24
	@ 600px	@ 4462.8 µm	2921.0 ± 32.5	1.11
	@ 700px	@ 5206.6 µm	3053.7 ± 30.0	0.98
	@ 800px	@ 5950.4 µm	3138.0 ± 35.3	1.13
	@ 900px	@ 6694.2 µm	3211.0 ± 43.7	1.36
	@ 1000px	@ 7438.0 µm	3261.9 ± 39.6	1.21
Canal thin			130.9 ± 13.1	10.0
Canal thick			348.1 ± 17.2	4.95
Cone length			5459.2 ± 82.6	1.51
			(deg)	(%)
Canal angle			127.5 ± 2.3	1.76
Cone angle			28.7 ± 1.2	4.21
Pitch angle			54.2 ± 2.3	4.23

Tab. 3 Comparison of the key parameters of original epoxy resin block – Plastic Practice Blocks .02 taper – Oblong for 15 file (Endo-Training-Bloc-J Dentsply Sirona, Ballaigues, Switzerland) with the 3D printed endodontic blocks. The asterisk (*) indicates insignificant differences of the respective parameters of the 3DP blocks in comparison with the original resin blocks.

dimension		Ratio of Means 3DP / Original (%)	one sample *t* – test		Coefficient of Variation ratio 3DP / Original (%)	Levene's test *p* – value
	true position (µm)		*p* – value	power		
Canal profile	@ 743.8 µm	103	= 0.010	0.777	56	= 0.018
	@ 1487.6 µm	98	= 0.003	0.907	34	> 0.001
	@ 2231.4 µm	97	> 0.001	1	27	> 0.001
	@ 2975.2 µm	95	> 0.001	1	22	> 0.001
	@ 3719.0 µm	94	> 0.001	1	26	> 0.001
	@ 4462.8 µm	94	> 0.001	1	27	> 0.001
	@ 5206.6 µm	94	> 0.001	1	27	> 0.001
	@ 5950.4 µm	93	> 0.001	1	35	= 0.003
	@ 6694.2 µm	92	> 0.001	1	20	= 0.037
	@ 7438.0 µm	92	> 0.001	1	48	= 0.027
Canal thin		96	= 0.055*	0.493	116	= 0.488*
Canal thick		111	> 0.001	1	113	= 0.272*
Cone length		90	> 0.001	1	42	= 0.050
		(%)			(%)	
Canal angle		102	> 0.001	0.958	81	= 0.392*
Cone angle		98	= 0.015	0.715	408	> 0.001
Pitch angle		93	> 0.001	1	105	= 0.876*

DISCUSSION

In our study, we fabricated 20 transparent endodontic blocks of the same design as the commercially available Plastic Practice Blocks .02 (Endo-Training-Bloc-J Dentsply Sirona, Ballaigues, Switzerland).

In previous studies (20–22), the endodontic resin blocks with a J-shaped artificial canal are described by the length, angle, and radius of curvature of the artificial canal. Nevertheless, especially in the case of determination of the canal angle, there are many different methods (according to Weine, Schneide, Luiten, etc.) (23) providing significantly different results, even for the same tested resin block. Thus, these methods are not sufficiently accurate and reproducible. Therefore, we used a larger number of clearly defined parameters (Figure 1) to precisely measure, copy, and 3D print the endodontic blocks. We measured 20 original resin blocks and used the mean values of the selected parameters to design the new 3DP blocks.

Despite the printing resolution of 16 μm per layer, the resulting roughness of the block surface was relatively high, preventing direct observation of the artificial canal in the optical microscope. Polishing with different gums and pastes did not bring any improvement. The use of Evetric Bond (Ivoclar Vivadent AG, Schaan, Liechtenstein) with straight stainless steel dental matrix led to the formation of a smooth transparent layer that allowed observation of the internal structures of the printed block with a minimum distortion.

To observe the artificial canals, the newly printed blocks also required removement of the support material, which turned out to be quite difficult. We used high pressure water, which is the recommended method by the printer manufacturer. Nevertheless, this method did not remove the support material from the artificial canal. In many studies involving the investigation of the resin blocks, water (11, 24), isopropyl alcohol (25), or different types of alcohols were used as irrigation solutions. For us, 96% ethanol worked best as it helped to disrupt and remove the partially alcohol soluble support material. We found that ethanol was even a better irrigant than NaOCl or EDTA (17). Furthermore, in order to fill canal with irrigant and ensure patency, the canals were instrumented with stainless-steel files. It was necessary to prebend the stainless-steel instruments to protect the canals from alternating the design during their instrumentation.

We proved a high reproducibility of the 3D printing process of the endodontic training blocks printed from acrylic resin (VeroClear-RGD810, Stratasys, Eden Prairie, USA) using the 3D precision printer Objet30 Pro (Stratasys, Eden Prairie, USA). The dimensional variability of the 3DP blocks was significantly lower (3–5 times) for most of the tested parameters. It is the most important study output because only the blocks with a low dimensional variability allow for a consistent and reproducible results of the tests of endodontic instruments. The accuracy of the 3DP blocks was also sufficient. Although the measured dimensions of the 3DP blocks were statistically significantly different from the dimensions of the original resin blocks, the maximum difference was 11% and can be easily eliminated by modifying the CAD model (available in the supplementary materials on the article web page). A limitation of this study is the effect on the artificial canal profile by removing the support material. Even with the use of a fine and pre-bent ISO 10 stainless steel K-file, the canal was straightened, which is a typical problem when using rotary files (26) and is shown by a decrease in the pitch angle and a relative increase in the values of the canal profile measured at distances of 100, 200, 300 and 400 px. The use of a finer tools – e.g. ISO 06 and 08 – could not remove the support material from the artificial canal. Also, the proximal and distal diameters of the artificial canal of the 3DP blocks were affected. Alternative possibilities of the support material removal from the artificial canals should be further investigated.

Despite certain difficulties associated with the elimination of the support material, PolyJet printing is currently the only available 3DP method that can print such narrow (100 μm) curved cavities. For comparison, the SLA (stereolithography) method does not allow the printing of supports from different material that that of the object printed, the FFD (filament feeder) 3DP method does not allow such a fine resolution (usually not less than 50 μm per layer, e.g., TRILAB DeltiQ 2 by TRILAB Group s.r.o., Hradec Králové, Czech Republic) and is also limited by the minimum width of the printed line (usually not less than 250 μm, e.g., TRILAB DeltiQ 2 by TRILAB Group s.r.o., Hradec Králové, Czech Republic), the SLS (selective laser sintering) method is limited by the grain size of the sintered material (usually not less than 100 μm, e.g., Polyamid 12 PA 2200 by EOS GmbH, Krailling, Germany).

CONCLUSION

3D polyjet printing is a promising method of manufacturing endodontic test blocks. Its main advantages are high reproducibility of printing and the possibility of producing artificial root canals of any desired shape.

The profiles of the 3D printed artificial canals showed statistically significantly lower dimensional variability (2–5 times) when compared with the original resin blocks.

The disadvantage of the printing method used is the difficult support material removal negatively affecting the profile of the printed artificial canal. Alternative methods to remove the support material should be further investigated.

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